IAC-11-A5.1.4

RESOLVE

Ground Truth for Polar Volatiles as a Resource

William E. Larson
NASA-Kennedy Space Center

Martin Picard
Canadian Space Agency

Gerald B. Sanders
NASA- Johnson Space Center

Anthony Colaprete
NASA- Ames Research Center

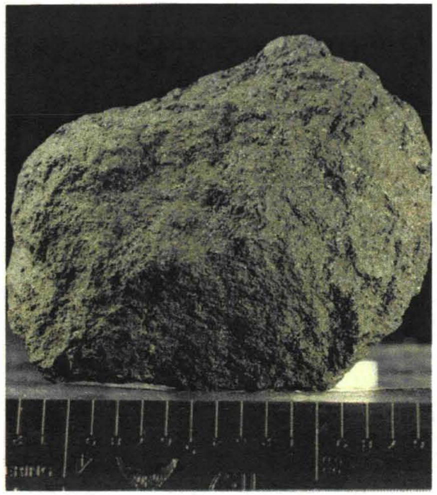
Richard C. Elphic
NASA- Ames Research Center

62nd International Astronautical Congress
Cape Town, South Africa
October 2011

william.e.larson@nasa.gov

Our Evolving Understanding of the Moon and its Resources

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



Apollo samples, 1969-1972 point to a bone dry Moon

In a 1961 paper, Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice

1961:

1970

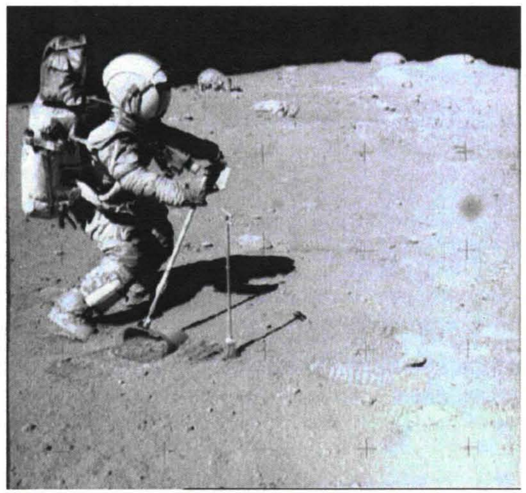
1994

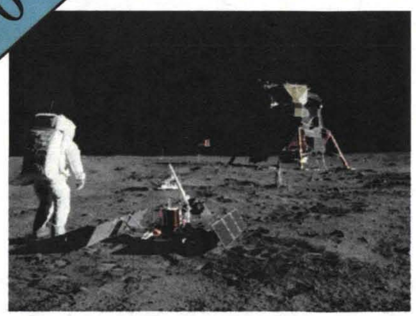
1998

2008

2009

2010





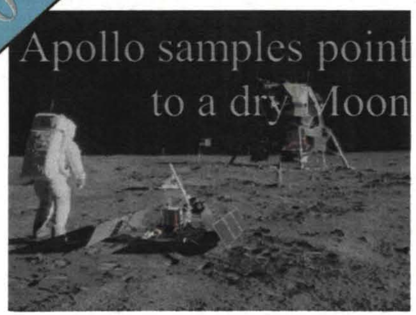
Our Evolving Understanding of the Moon and its Resources

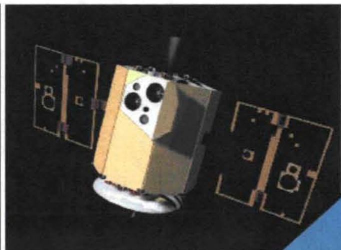
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

Missions to the Moon in the 1990's provided intriguing data that suggested the permanently shadowed regions of the Moon may harbor water ice and other volatiles

1961: 1970 1994 1998 2008 2009 2010

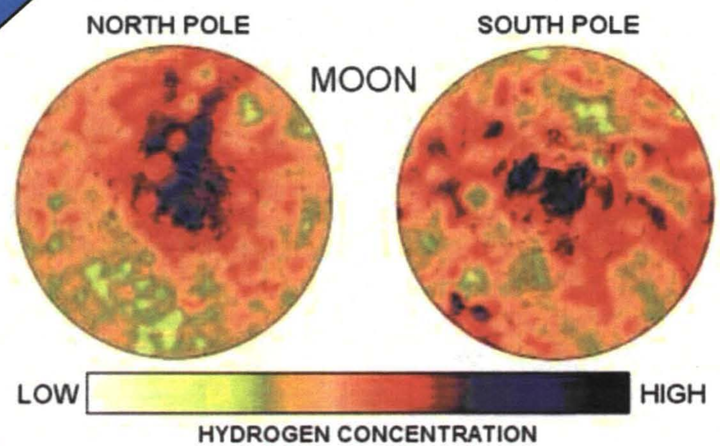
Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice





Clementine Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles

Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow



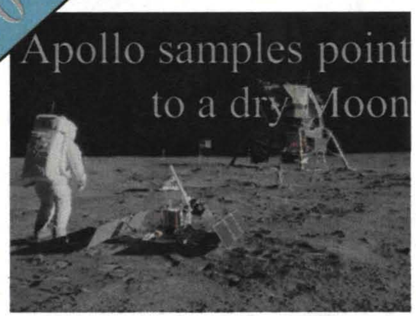
Our Evolving Understanding of the Moon and its Resources

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

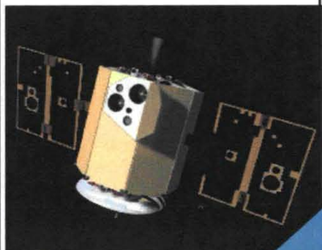
Conclusions drawn from Clementine and Lunar Prospector regarding lunar water ice was vigorously debated.

1961; 1970; 1994; 1998; 2008; 2009; 2010

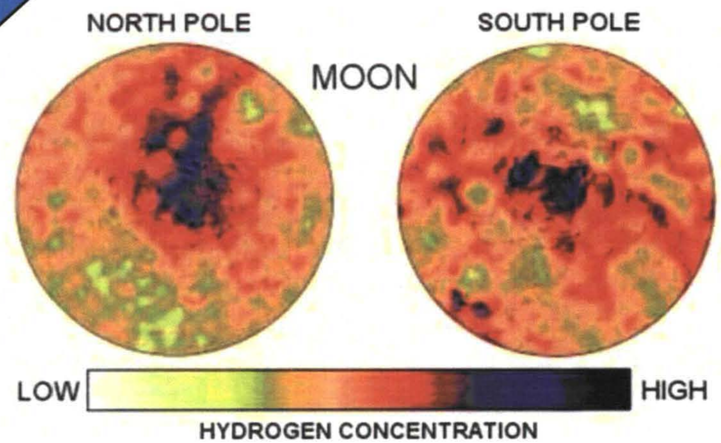
Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice



Clementine Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles



Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow



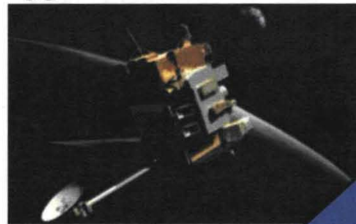
Planetary Scientist, Larry Taylor, says he will "eat his shorts if there is water on the moon."

Our Evolving Understanding of the Moon and its Resources

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

1961: 1970 1994 1998 2008 2009 2010

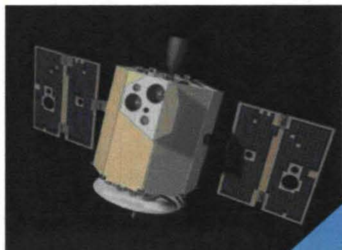
Integrated data sets from instruments on LRO support the existence of large quantities of water ice in the PSRs and in partially sunlit regions



Synthetic Aperture Radar on Chandrayaan 1 returns data that is consistent with water ice in the PSR's

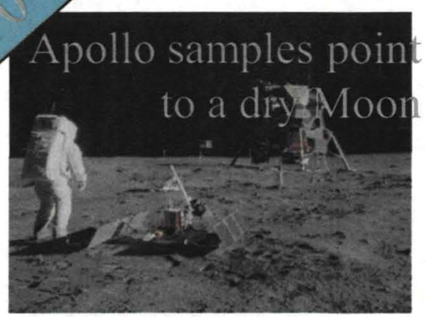
LCROSS impacts Cabeus A and clearly detects significant quantities of water in the ejecta

Clementine's Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles



Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow

Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice



LCROSS & LRO Definitively Prove Existence of Volatiles at the Lunar Poles

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

					Instrument			
	Column Density (# m^{-2})	Relative to H2O(g) (NIR spec only)	Concentration (%)	Long-term Vacuum Stability Temp (K)	UV/Vis	NIR	LAMP	M3
CO	1.7e13±1.5e11		5.7	15			x	
$H_2O(g)$	5.1(1.4)E19	1	5.50	106		x		
H_2	5.8e13±1.0e11		1.39	10			x	
H_2S	8.5(0.9)E18	0.1675	0.92	47	x	x		
Ca	3.3e12±1.3e10		0.79				x	
Hg	5.0e11±2.9e8		0.48	135			x	
NH_3	3.1(1.5)E18	0.0603	0.33	63		x		
Mg	1.3e12±5.3e9		0.19				x	
SO_2	1.6(0.4)E18	0.0319	0.18	58		x		
C_2H_4	1.6(1.7)E18	0.0312	0.17	~50		x		
CO_2	1.1(1.0)E18	0.0217	0.12	50	x	x		
CH_3OH	7.8(42)E17	0.0155	0.09	86		x		
CH_4	3.3(3.0)E17	0.0065	0.04	19		x		
OH	1.7(0.4)E16	0.0003	0.002	>300 K if adsorbed	x	x		x
H_2O (adsorb)			0.001-0.002					x
Na		1-2 kg		197	x			
CS					x			
CN					x			
$NHCN$					x			
NH					x			
NH_2					x			

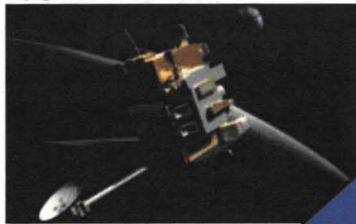
Volatiles comprise possibly 15% (or more) of LCROSS impact site regolith

Our Evolving Understanding of the Moon and its Resources

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

Larry Taylor is served a cake decorated as a pair of shorts at a Lunar Planetary Institute meeting

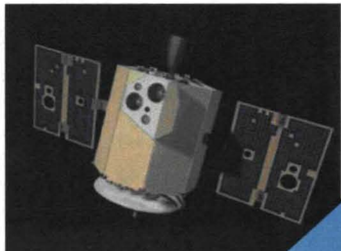
Integrated data sets from instruments on LRO support the existence of large quantities of water ice in the PSRs and in partially sunlit regions



Synthetic Aperture Radar on Chandrayaan 1 returns data that is consistent with water ice in the PSR's

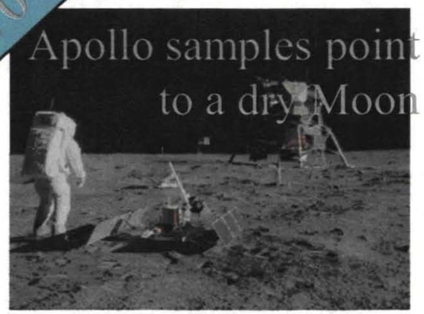
LCROSS impacts Cabeus A and clearly detects significant quantities of water in the ejecta

Clementine's Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles



Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow

Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice



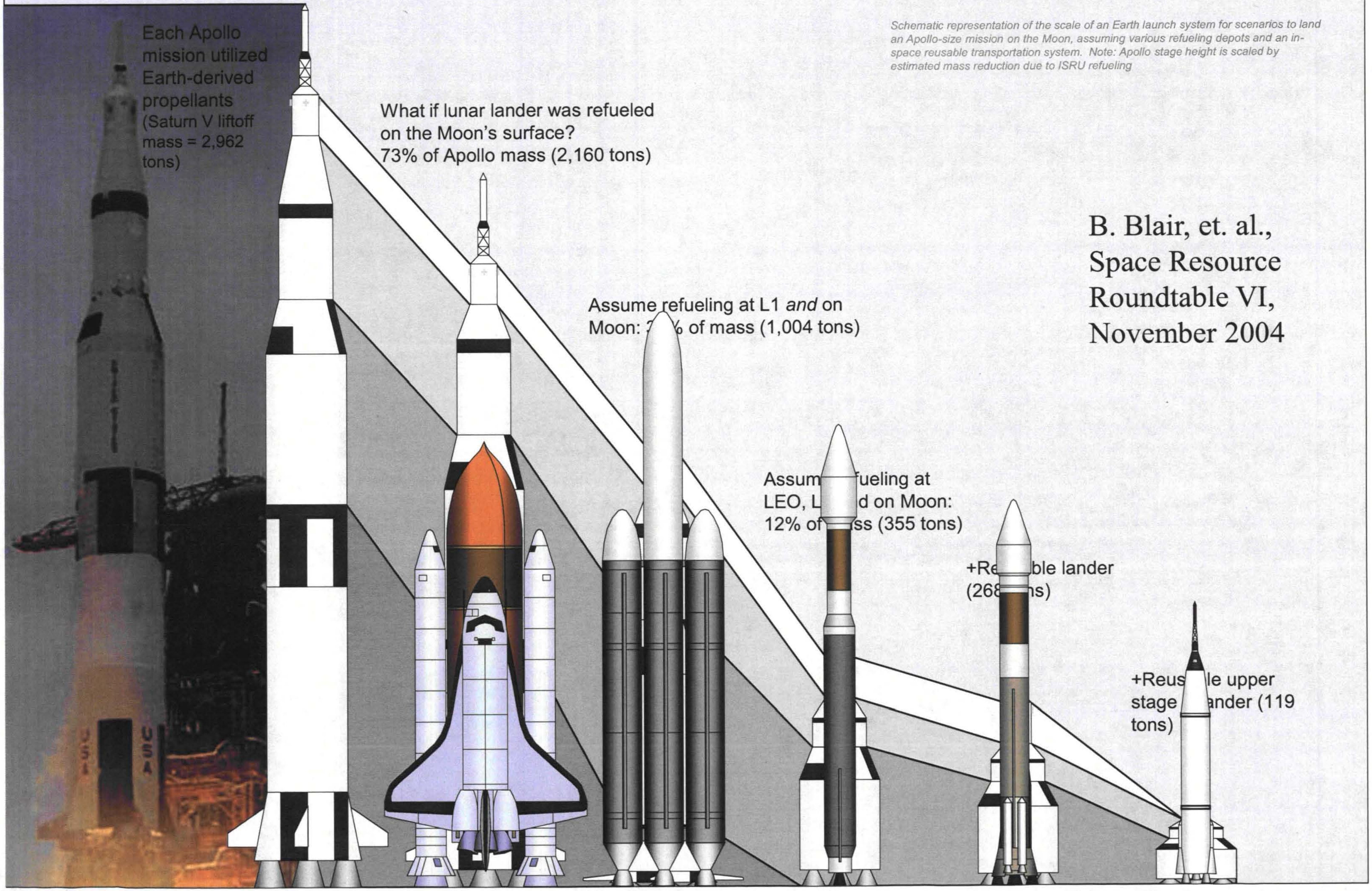
Apollo samples point to a dry Moon

1961: 1970 1994 1998 2008 2009 2010

Importance of Lunar Volatiles as a Resource

- Water is Life
  - Oxygen to breath
  - Water to drink
  - Water for cooling systems
  - Water for radiation shielding
  - Water for plants
- Volatiles can be used to manufacture propellant
  - Water is an easy form for the transportation of hydrogen & oxygen
  - Water can be converted into hydrogen and oxygen using abundant solar power in orbit
  - Hydrogen & Oxygen can be liquefied in space and stored in propellant depot
  - Orbital depots open up a commercial market for propellants
  - Alternatively, the hydrogen from the water can be combined with plentiful carbon monoxide to make methane, another useful propellant.
- Harvesting resources at our destinations can dramatically change the our mission architectures.

Propellant from the Moon will revolutionize our current space transportation approach



What's the Next Step?

- We now know with certainty that there are volatiles at one spot on the moon.
- Comparison's of orbital instrument data with the LCROSS plume seem to suggest that the water is not evenly distributed.
- Until we know the distribution and accessibility of the volatiles don't really know if we have a usable resource.
- A "Ground Truth" surface mission is the next logical step.
- RESOLVE is the payload that NASA and the CSA are designing to answer these questions

Surface Mission Drivers

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

- **Given: There are potentially substantial hydrogen rich resources on the Moon…**
- **Then: We must gain the necessary knowledge to guide future mission architectures to allow effective utilization of in-situ resources to their fullest extent and optimum benefit.**

- **Understand the resources**
  - What resources are there?
  - How abundant is each resource?
  - What are the horizontal and vertical distributions and hetero/homogeneity?
  - How much energy is required to locate, acquire and evolve/separate the resources?

- **Understand environment impact on extraction and processing hardware**
  - What is the local temperature, illumination, radiation environment?
  - What are the physical/mineralogical properties of the local regolith?
  - Are there extant volatiles that are detrimental to processing hardware or humans?
  - What is the impact of significant mechanical activities on the environment?

- **Design and utilize hardware to the maximum extent practical that has applicability to follow-on ISRU missions**
  - Can we effectively separate and capture volatiles of interest?
  - Can we execute repeated processing cycles (reusable chamber seals, tolerance to thermal cycles)?

RESOLVE Mission Requirements

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

Primary Mission:

✓ **Verify the existence of and characterize the constituents and distribution of water and other volatiles in lunar polar surface materials**

- **Map the surface distribution of hydrogen rich materials** (Neutron Spectrometer, Near-IR Spectrometer)
- Extract 1m core sample with minimal loss of volatilesfrom selected sites (Drill /AugerSubsystem)
  - to a depth of 1m
- **Heat multiple samples from each core to drive off volatiles for analysis** (OVEN Subsystem)
  - from 100°K to 473°K
  - from 0 up to 100 psia (reliably seal in aggressively abrasive lunar environment)
- **Determine the constituents and quantities of the volatiles extracted** (LAVA Subsystem)
  - Hope to find and quantify H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2
  - Survive limited exposure to HF, HCl, and Hg

Secondary Mission:

✓ **Demonstrate the ISRU Hydrogen Reduction Process to extract oxygen from lunar regolith**

- **Heat sample to reaction temperature** (OVEN Subsystem)
  - from 473°K to 1173°K
- **Flow H_2 through regolith to extract oxygen in the form of water** (OVEN Subsystem)
- **Capture, quantify, and display the water generated** (LAVA Subsystem)

Major RESOLVE Subsystems

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

- The **Neutron Spectrometer Subsystem** will be used to verify the presence of hydrogen rich materials and then map the distribution of these materials to assist in sample site selection and better understand the morphology of the resource. The Near Infrared (NIR) Spectrometer instrument will be used to scan the immediate vicinity of the drill site before and during drill/auger operations to look for near real-time changes in the properties of the materials exposed during the drilling process.

- The **Near Infrared (NIR) Spectrometer Subsystem** will be used to provide an additional means of surveying the surface and immediate excavation site for water and other volatiles. Provides surface and regolith mineral context. The Near Infrared (NIR) Spectrometer instrument will be used to scan the immediate vicinity of the drill site before and during drill/auger operations to look for near real-time changes in the properties of the materials exposed during the drilling process.

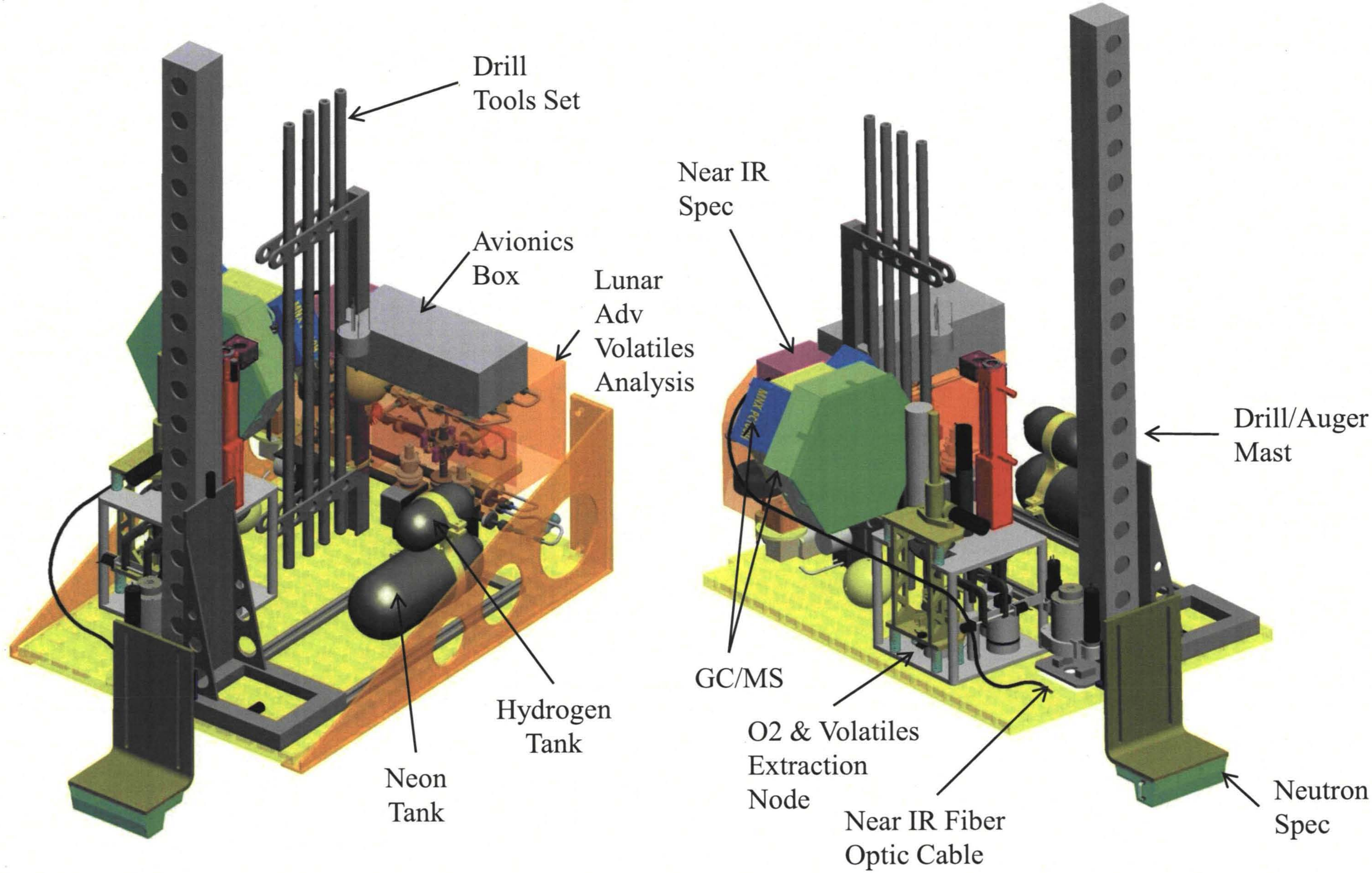
- The **Drill Subsystem** includes the hardware to physically excavate/extract regolith from the lunar surface to a depth of 1 m and perform any type of preparation necessary (grinding, crushing, sieving, etc.) before delivering the sample to one or more reactor chambers for further processing by the Reactor Subsystem. This subsystem will be provided by the Canadian Space Agency (CSA) through a partnering agreement and integrated into the RESOLVE. The excavation device will be instrumented to measure forces/displacements etc. to determine critical bulk properties of the regolith.

- The **O**xygen and **V**olatile **E**xtraction **N**ode **(OVEN)** Subsystem will accept samples from the Drill Subsystem and will evolve the volatiles contained in the sample by heating the regolith in a sealed chamber and will also extract oxygen from the remaining regolith sample. Each sample will be sealed in the OVEN chamber and heated up to 150°C to evolve volatiles (H_20, CO, etc.). At most 1 (one) sample from each core will continue to be heated up to ~900°C and be subjected to hydrogen reduction processing

- The **Lunar Advanced Volatile Analysis (LAVA) Subsystem** will accept the effluent gas/vapor from the OVEN Subsystem and analyze that effluent gas using gas chromatograph and/or mass spectrometer sensor technologies. LAVA Subsystem will design, develop, test, and provide all of the fluid system hardware necessary to support OVEN Subsystem and LAVA Subsystem instrumentation operations. The system will measure constituents below atomic number 70 (including H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2, etc.).

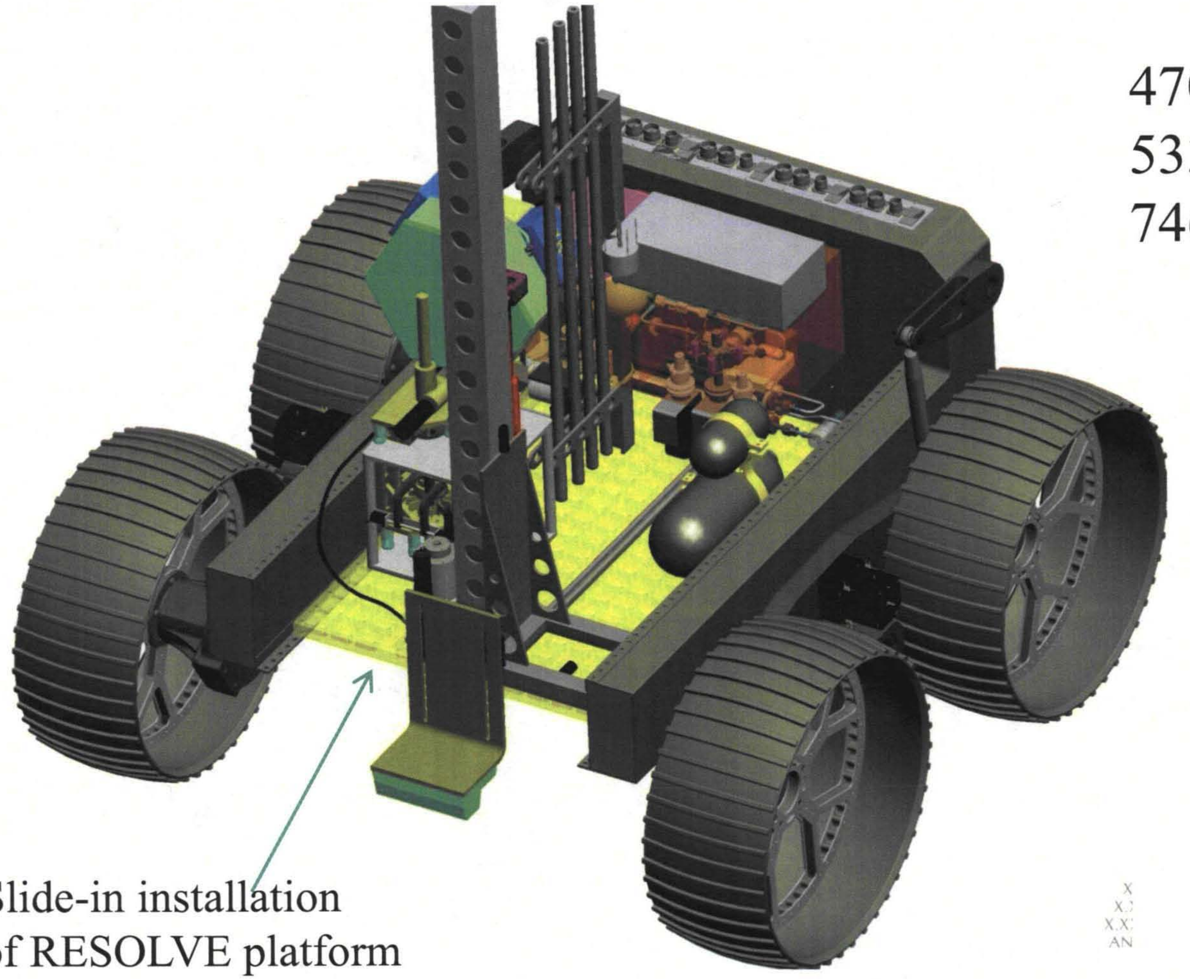
RESOLVE Payload Layout

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



RESOLVE Integrated with CSA Rover

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



470mm Length
533mm Width
746mm Height

Slide-in installation
of RESOLVE platform
To CSA Rover

Planning the Mission: Where should we land?

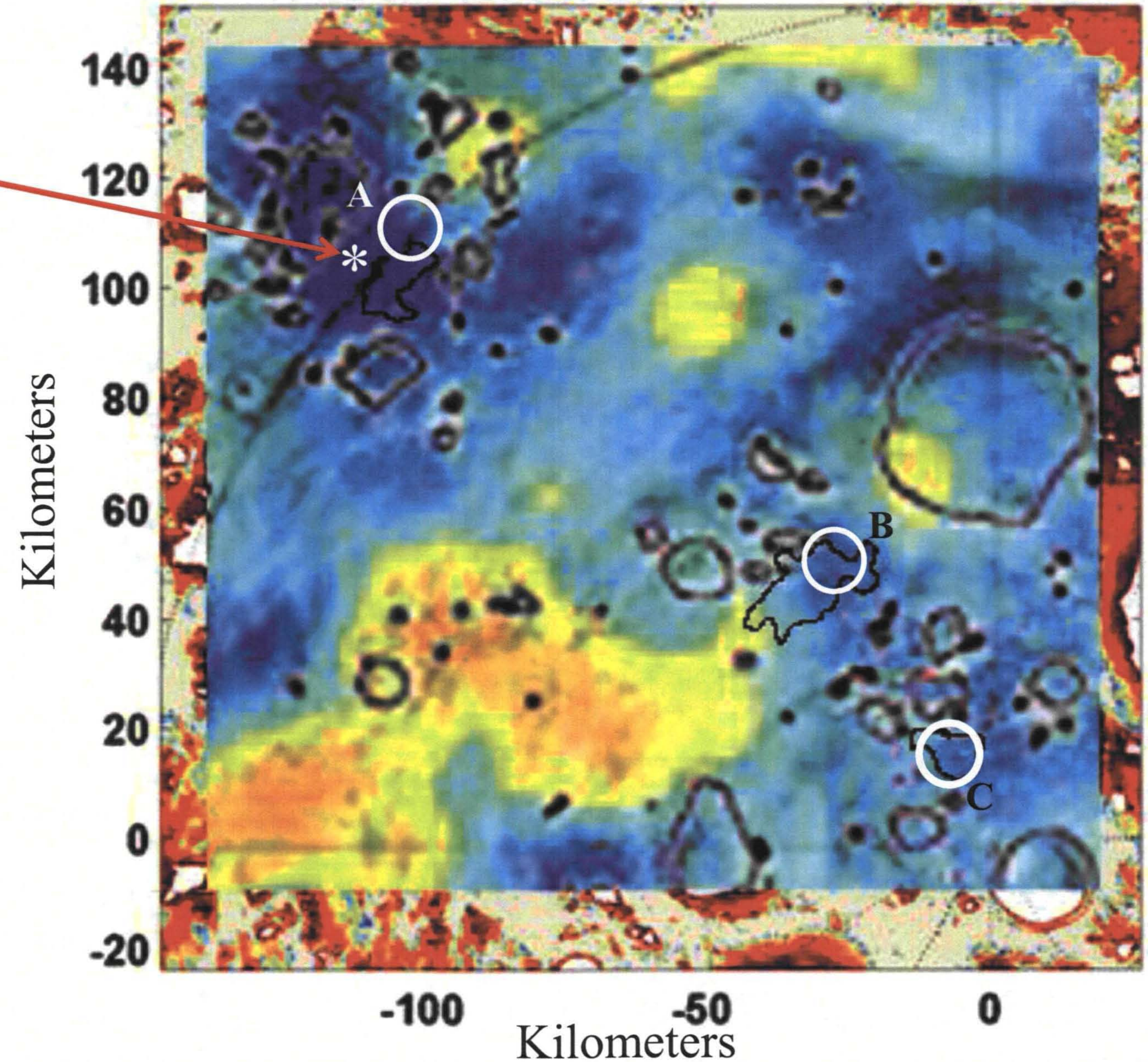
- Permanent Shadowed Craters?
  - LRO radar data suggests large, thick deposits of water ice in some of the Permanently Shadowed Craters
  - However, temperatures are extremely low (<40K), and a mission of any significant duration would probably require a nuclear energy source.
    - Mission would be prohibitively expensive for our current budget environment.
- Partially sunlit regions?
  - Lunar Exploration Neutron Detector (LEND) suggests that there are areas of neutron suppression (indicator of hydrogen) outside of the permanently shadowed regions.
  - David Paige and the DIVINER radiometer team published results indicating that there are many areas in the polar regions that have subsurface temperatures (<100K) that would support the existence of water ice.
  - Solar powered missions are more affordable and the operating environment for hardware is much less harsh.
  - Perhaps a location like this would make it easier to set up a future mining operation on the Moon if the resources were plentiful enough.

RESOLVE Mission Options – Potential South Pole Landing Sites

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

Neutron Depletion

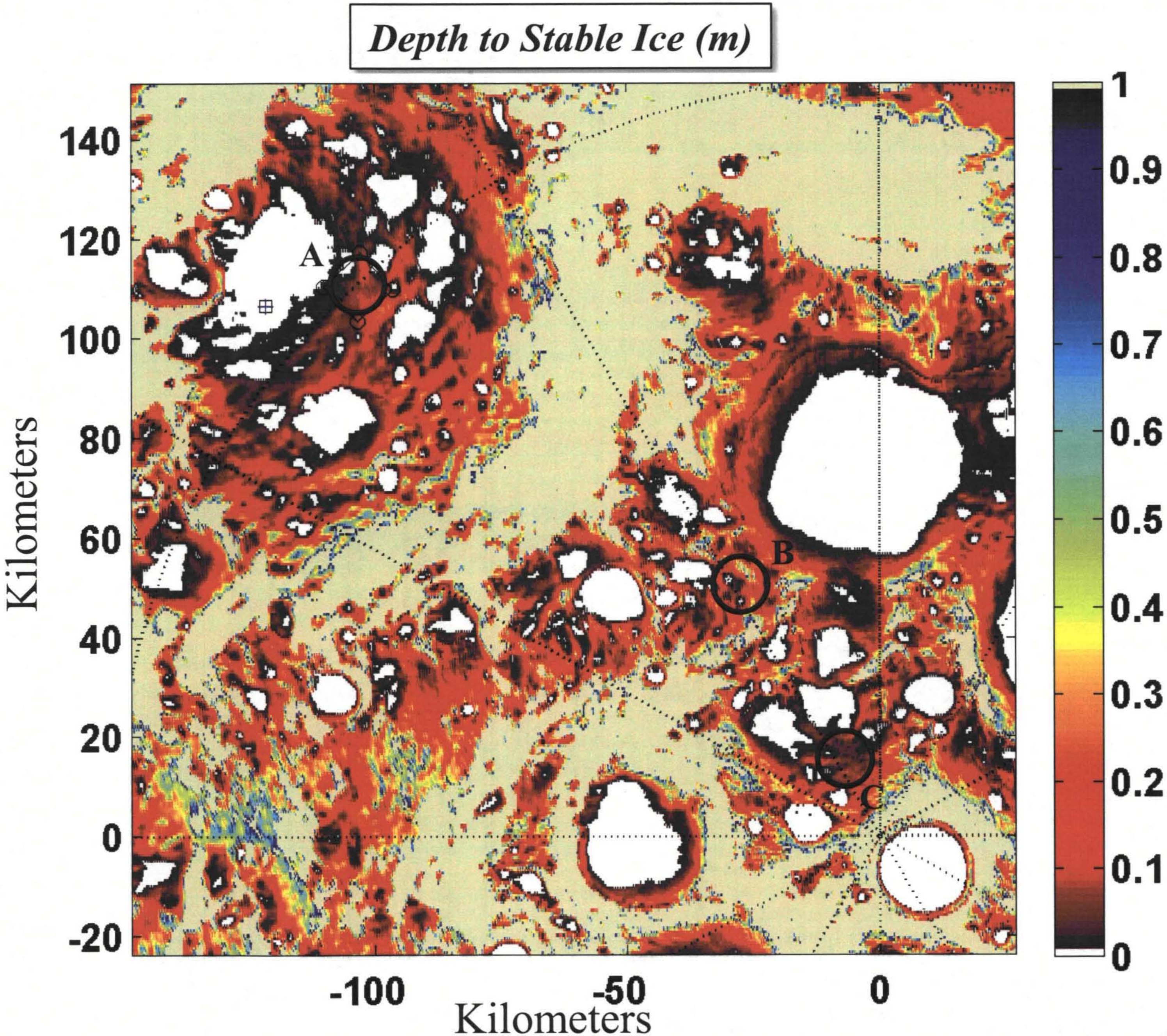
LCROSS impact site



Dark blue represent the areas of highest neutron suppression

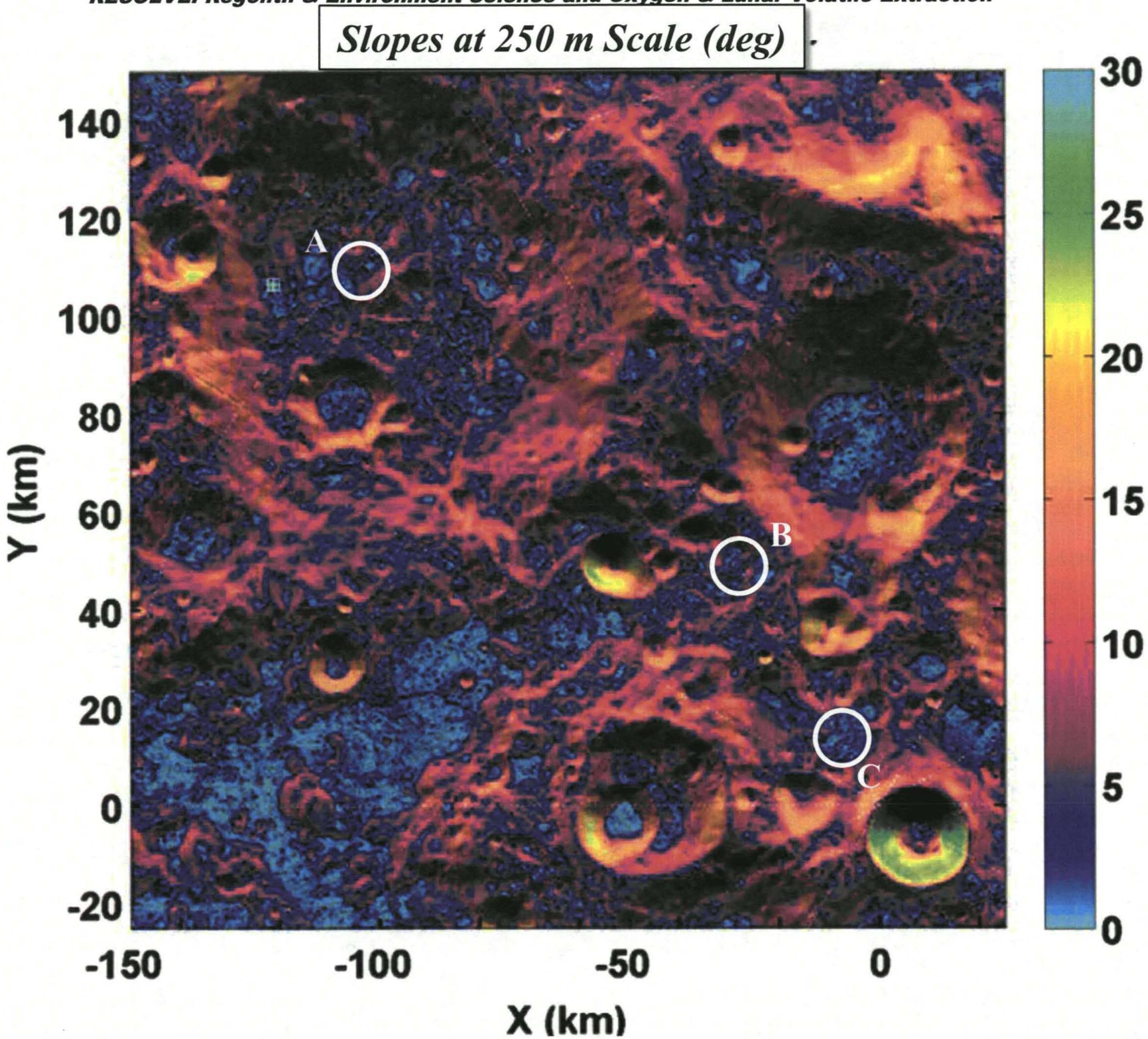
Circles A, B & C selected for closer examination

RESOLVE Mission Options – Potential South Pole Landing Sites



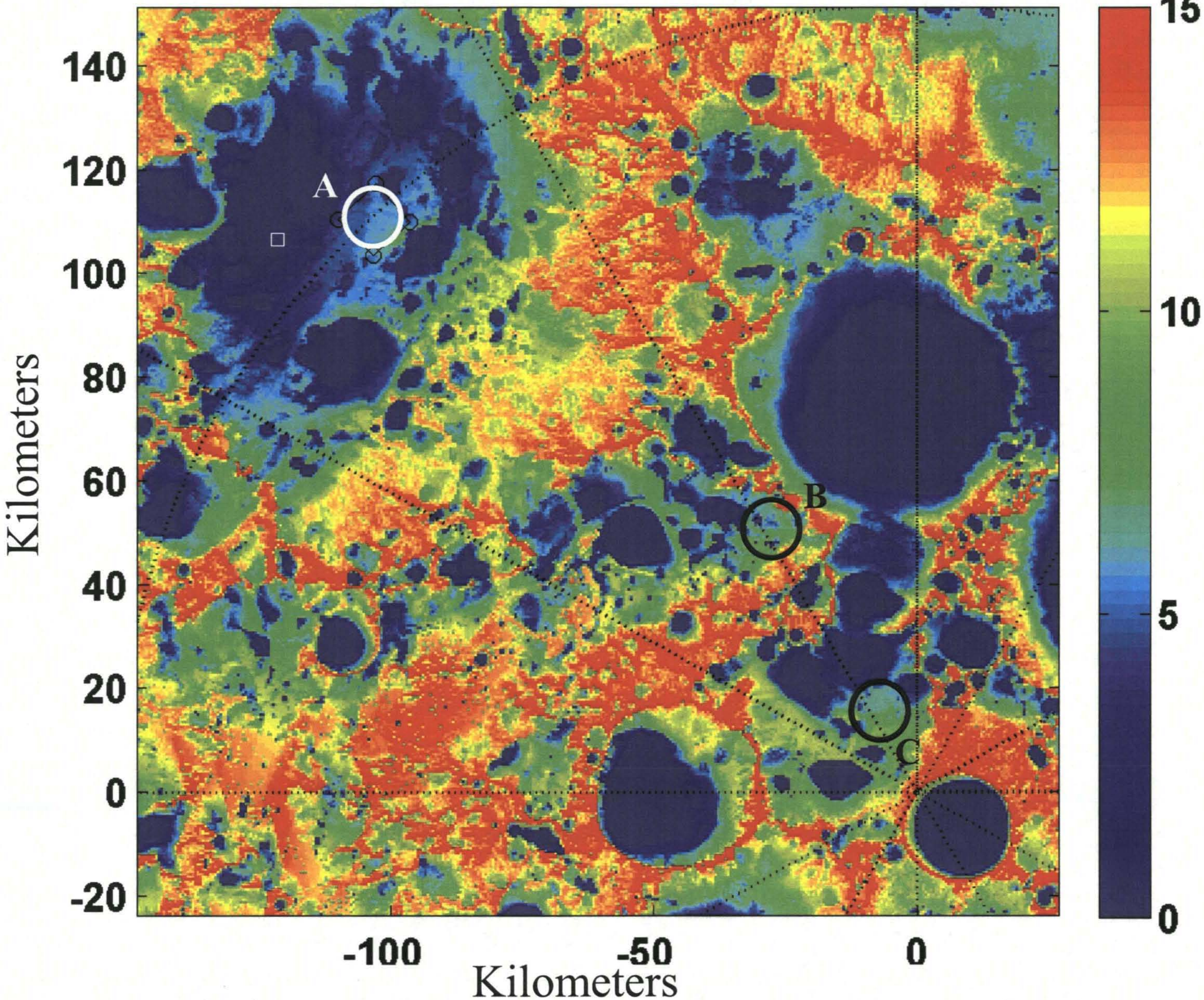
RESOLVE Mission Options – Potential South Pole Landing Sites

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



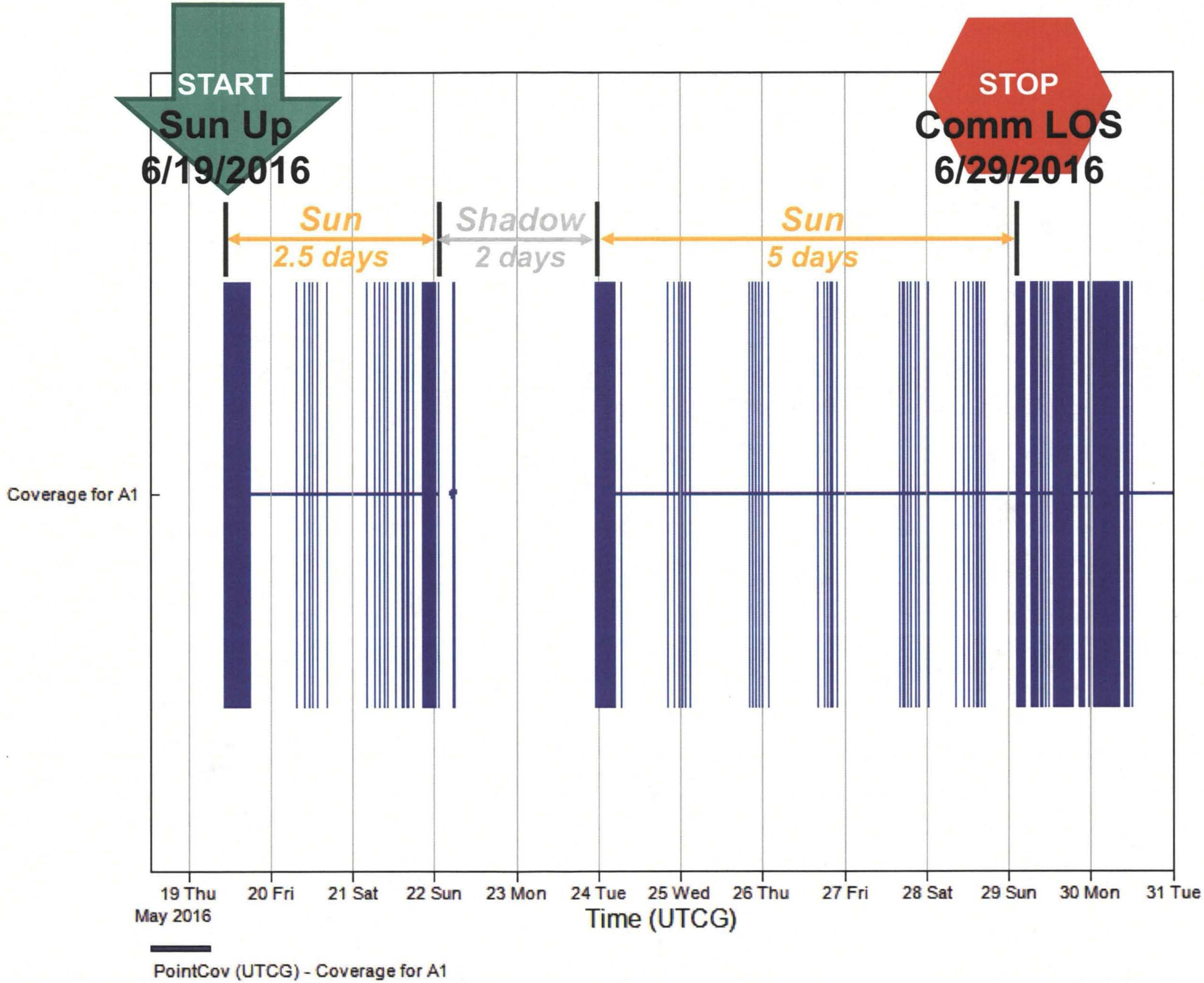
RESOLVE Mission Options – Potential South Pole Landing Sites

Maximum Days of Sunlight Using LOLA DEM



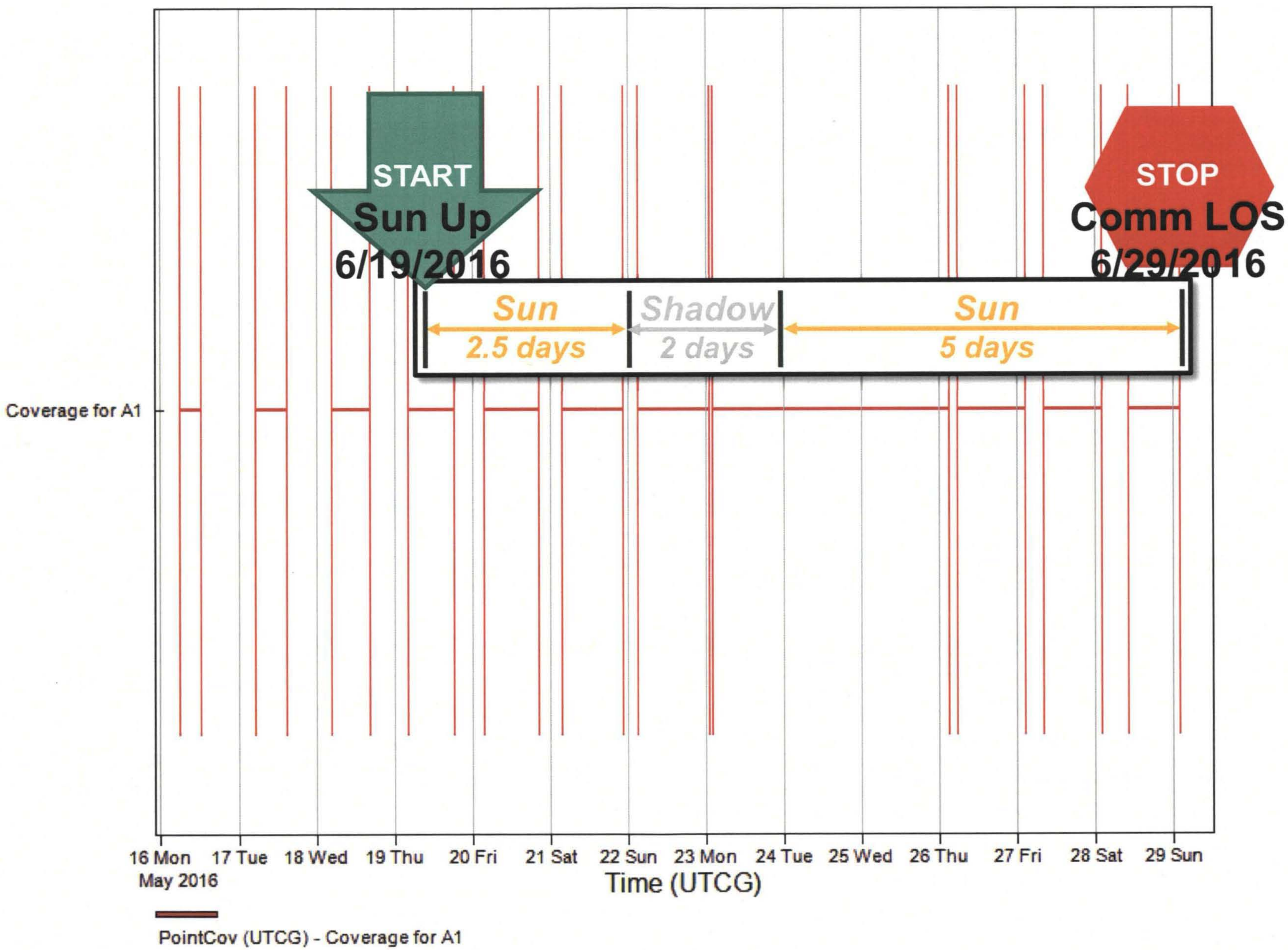
Sunlight Availability
(Cabeus Site A1, May 2016)

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



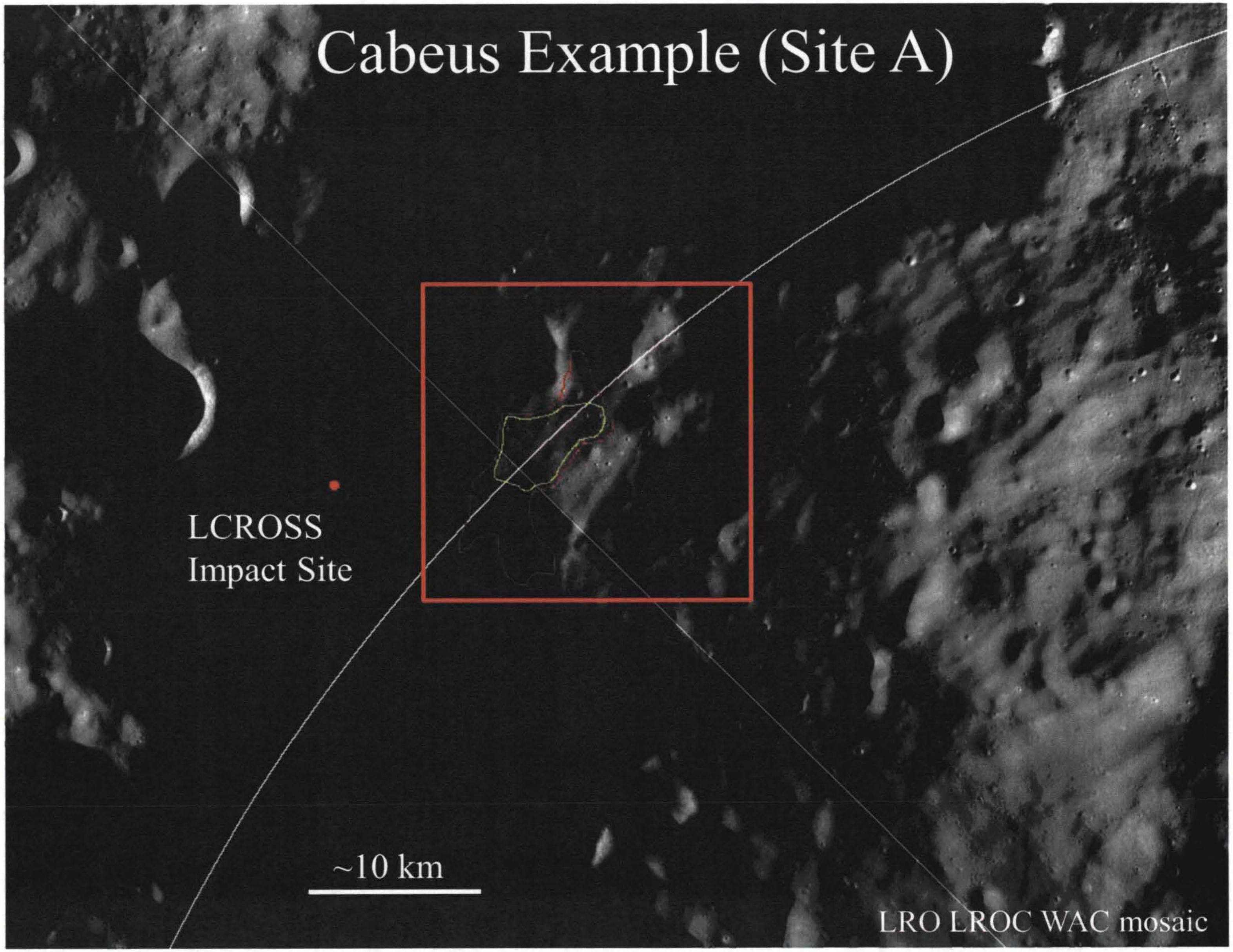
Communications Availability
(DTE McMurdo, Cabeus Site A1, May 2016)

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



RESOLVE Mission Options – Potential South Pole Landing Sites

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



Sun and Shadow Ops

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

SUN (2.5 days)

- **Checkout**
  - *6.17 hrs*

- **1st Navigation 0.6 km**
  - *3.88 hrs, 0.6 km total*
- **Drill 1st Hole 4.33 hrs**
  - *Two 0.5m Augers (1-2)*
  - *One 1.0m Core (1)*
- **Process Segments (1-8)**
  - *8 segments, 26.84 hrs*

- **2nd Navigation 0.6 km**
  - *3.88 hrs, 1.2 km total*
- **Drill 2nd Hole 4.33 hours**
  - *Two 0.5m Augers (3-4)*
  - *One 1.0m Core (2)*
- **Process Segments (9-10)**
  - *2 segments, 9.59 hrs*

SHADOW (2 days)

- **Hibernate**
  - *48 hrs*
- *Consider using this "down time" to downlink detailed RESOLVE data (pics, detailed plant data, etc.)*

SUN (5 days)

- **Battery Recharge**
  - *6.8 hrs*

- **3rd Navigate 0.6 km**
  - *3.88 hrs, 1.8 km total*
- **Drill 3rd Hole 4.33 hrs**
  - *Two 0.5m Augers (5-6)*
  - *One 1.0m Core (3)*
- **Process Segments (11-15)**
  - *5 segments, 19.85 hrs*
  - *1st H2 Reduction*

- **4th Navigate 0.2 km**
  - *2.29 hrs, 2.0 km total*
- **Drill 4th Hole 4.33 hrs**
  - *Two 0.5 m Augers (7-8)*
  - *One 1.0m Core (4)*
- **Process Segments (16-20)**
  - *5 segments, 19.85 hrs*
  - *2nd H2 Reduction*

- **5th Navigate 1.0 km**
  - *5.47 hrs, 3.0 km total*
- **Drill 5th Hole 4.33 hrs**
  - *Two 0.5m Augers (9-10)*
  - *One 1.0m Core (5)*
- **Process Segments (21-25)**
  - *5 segments, 18.41 hrs*
  - *3rd H2 Reduction*

MISSION SUMMARY

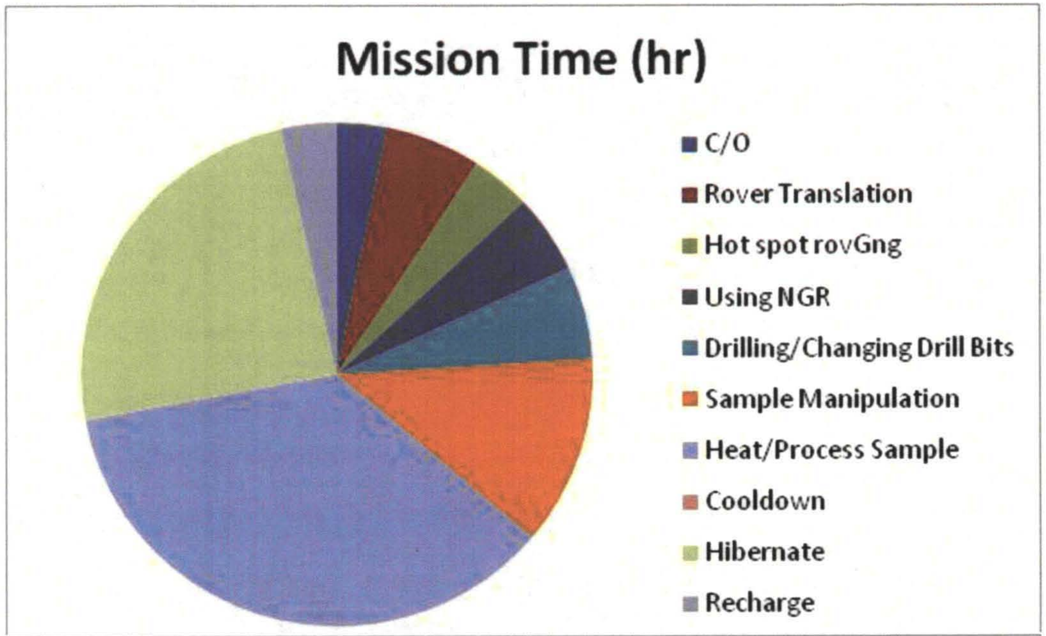
- Mission Length 9.5 days
  - 2.5 days Sun
  - 2.0 days Shadow
  - 5.0 days Sun
  - 8.2 days of Scheduled Activities
  - 1.3 days of Reserve Time
- Samples Processed
  - 25 processed at 150 deg C
  - 3 processed at 900 deg C
- Navigation
  - 5 navigation periods
  - Distance traveled is 3.0 km
- Drilling
  - Ten 0.5 m Augers
  - Five 1.0 m Cores

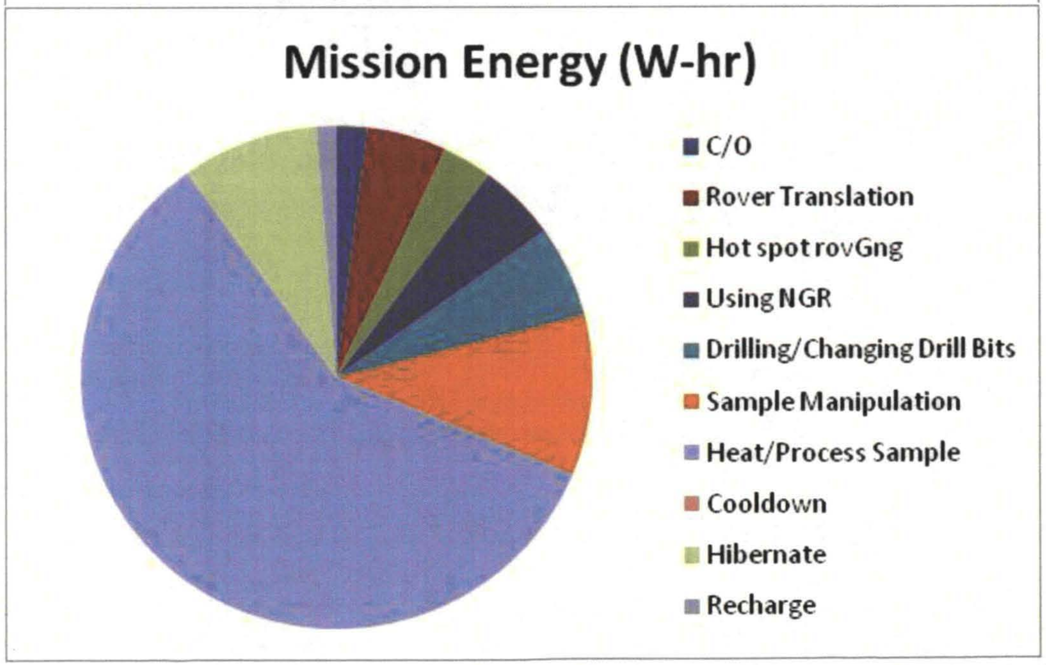
Time & Energy by Mission Function

(2.5 days Sun, 2 days Shadow, 5 days Sun)

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

	time (hr)	energy (W-hr)
C/O	6.17	684.77
Rover Translation	11.90	1754.76
Hot spot rovGng	7.50	1105.50
Using NGR	10.00	1765.00
Drilling/Changing Drill Bits	11.65	2056.23
Sample Manipulation	24.01	3620.82
Heat/Process Sample	70.53	20603.69
Cooldown	0.00	0.00
Hibernate	48.00	3024.00
Recharge	6.81	429.21
sum (hrs)	196.57	35043.97
sum (days)	8.190567	

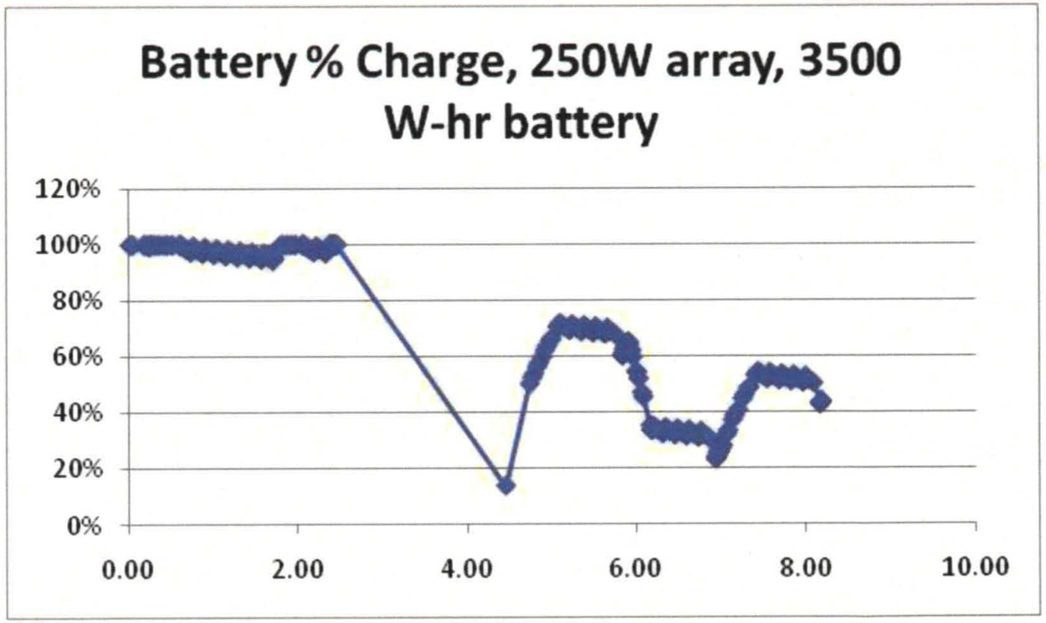




Time, Energy & Battery State of Charge by Segment
(2.5 days Sun, 2 days Shadow, 5 days Sun)

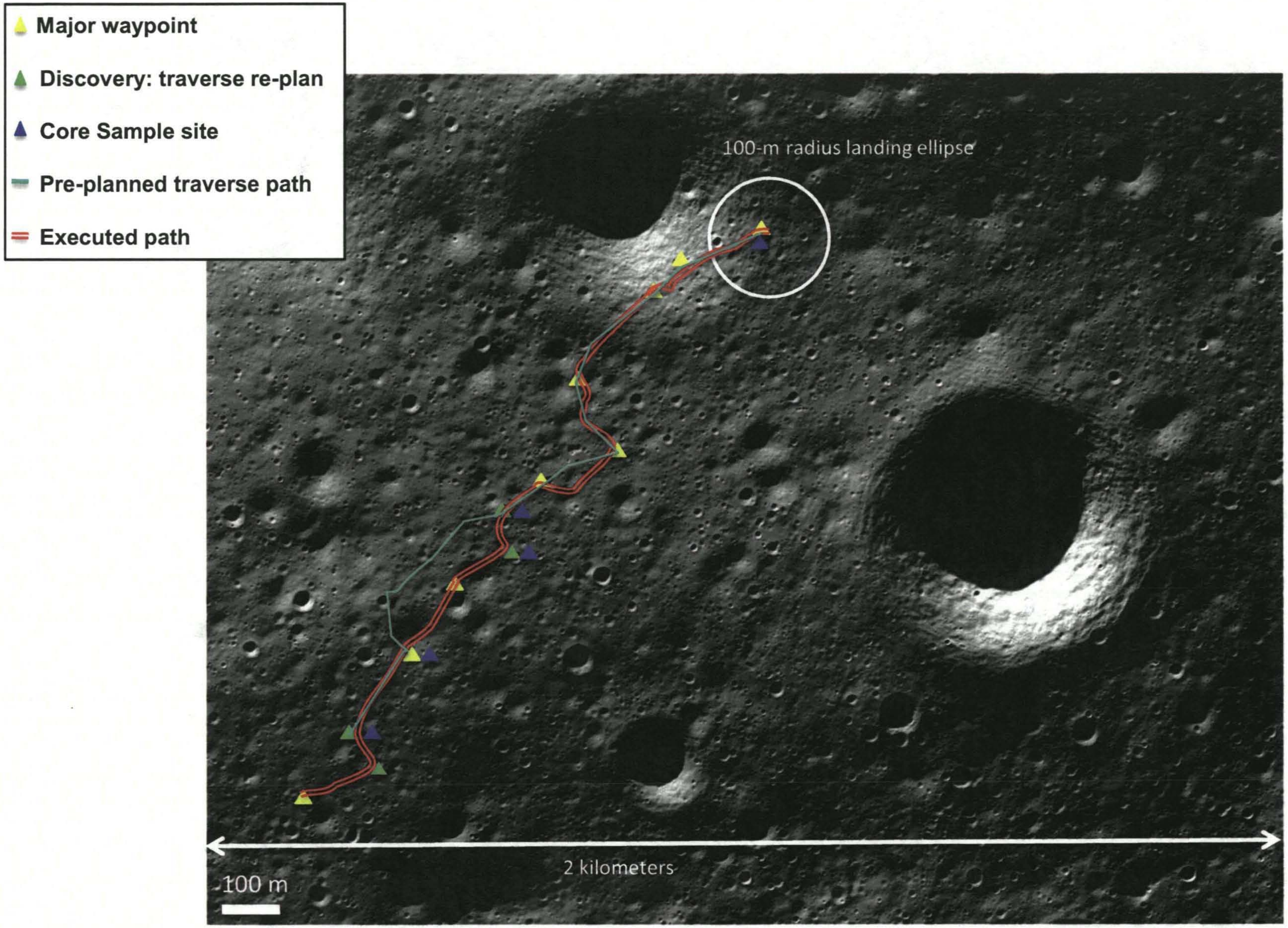
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

	time (hr)	energy (W-hr)
C/O	6.17	684.77
Nav 1	3.88	572.05
Drill 1	4.33	764.25
Process 1	26.84	6831.09
Nav 2	3.88	572.05
Drill 2	4.33	764.25
Process 2	9.59	2142.65
Hibernate + Recharge	54.81	3453.21
Nav 3	3.88	572.05
Drill 3	4.33	764.25
Process 3	19.85	5156.07
Nav 4	2.29	338.08
Drill 4	4.33	764.25
Process 4	19.85	5156.07
Nav 5	5.47	806.02
Drill 5	4.33	764.25
Process 5	18.41	4938.63
sum (hr)	196.57	35043.97
sum (days)	8.190567	



Notional Traverse Plan On Cabeus Floor

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



The Path Foward

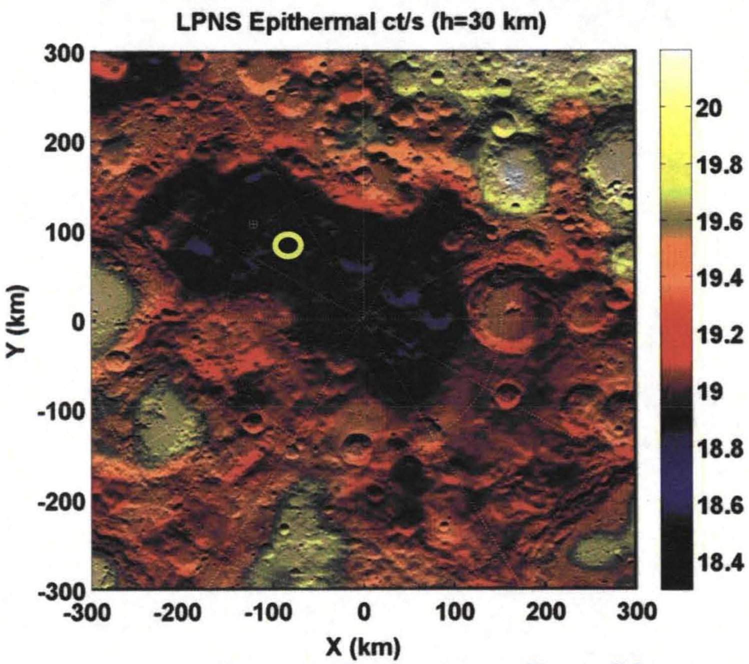
- RESOLVE and Rover Ground Demonstration Units (GDU)have completed their 90% design reviews and fabrication has begun
- Flight software development is underway
- Ground Development Units will used to conduct a mission simulation at a Lunar Analog Site (Mauna Kea, Hawaii) in the Summer of 2012.
- Flight Test Unit design begins this spring after initial integrated tests of RESOLVE GDU
- Goal is to have Flight Test Unit ready to go into thermal, vacuum and vibration testing by the fall of 2013.
- Hopefully, Commercial Lander capabilities will be coming on line in the 2014-15 timeframe due to the Google Lunar X-Prize.

"Sun&Shadow" Solar/Battery Rover Architecture

(Version 2.1, 2011-6-23)

- **Destination:** Moon South Pole
- **Site:** Cabeus A1
  - Latitude -85.75 deg
  - Longitude -45 deg
- **Surface Mission Duration:** 9.5 days (7.5 w/ sun)
- **Primary Spacecraft:** Rover
- **Power Strategy:** Solar PV + Battery
  - Solar Array 250 We
  - Secondary Battery 3500 W-hr
- **Comm. Strategy:** Direct via McMurdo/Troll
- **Survey Track:** 3,000 m
- **Payload:**
  - Drill 5x1m core, 10x0.5m auger
  - ISRU Reactor 25@150C, 3@900C ISRU
  - Gas Chrom. / Mass Spec. 25 samples
  - Neutron Spectrometer 3000m
  - Near-IR Spectrometer 3000m, 10 auger cuttings
- **Mission Energy:** 48,500 W-hr available
- **Mission Ave. Power:** 178 W predicted
- **Payload Mass:** 72 kg
- **Rover+P/L Mass:** 243 kg
- **Landed Mass:** 1285 kg
- **Wet Mass @ TLI:** 3,476 kg
- **Launch Vehicle Class:** Atlas V 411

Field Testing Rover Prototype



Cabeus South Pole Landing Site


QUESTIONS?
REGOLITH & ENVIRONMENT SCIENCE & OXYGEN & LUNAR VOLATILE EXTRACTION
RESOLVE